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A Dalitz Plot Analysis of $D^0 \to \pi^-\pi^+\pi^0$ Decays in CLEO II.V*

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Abstract

Using the $9 fb^{-1}$ data sample collected with the CLEO II.V detector at the Cornell Electron Storage Ring, we have studied the resonant substructure of the Cabibbo suppressed decay $D^0 \to \pi^-\pi^+\pi^0$. We observe significant contributions from the $\rho^-\pi^+$, $\rho^+\pi^-$, $\rho^0\pi^0$, and non-resonant channels, and present preliminary results of the amplitudes, phases, and fit fractions for these sub-modes. No evidence for the $\sigma(500)$ or more massive ρ resonances was found. We observe no CP violation, finding $\mathcal{A}_{CP} = 0.01^{+0.09}_{-0.07} \pm 0.09$.

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I. INTRODUCTION

A. Motivation

Three-body decays provide a rich laboratory in which to study the interference between intermediate state resonances, and can provide a direct probe of final state interactions. When a particle decays into three or more daughters, intermediate resonances dominate the decay rate and will cause a non-uniform distribution of events in phase space when analyzed using a "Dalitz plot" technique.[1] Since all events of a particular decay mode have the same final state, multiple resonances at the same location in phase space will interfere. This provides the opportunity to experimentally measure both the amplitudes and phases of the intermediate decay channels, which in turn allows us to calculate their fit fractions as well as set limits on CP violating asymmetries.

This paper describes a study of the underlying structure in the decay $D^0 \to \pi^-\pi^+\pi^0$, and is motivated in part by E791's recent work on $D^+ \to \pi^-\pi^+\pi^+$ which found significant evidence for a broad neutral scalar resonance, the $\sigma(500)$.[3]

Since $D^0 \to \pi^-\pi^+\pi^0$ is a CP eigenstate, we also look for CP violation. With no CP violation, $D^0 \to \rho^+\pi^-$ should have the same amplitudes and phases as $\overline{D^0} \to \rho^-\pi^+$. Recent theoretical works suggest that CP violation in $D^0 \to \pi^-\pi^+\pi^0$ may be as large as 0.1%. [4, 5].

B. Three Body Decays

In this analysis we are studying the decay of a spin zero D into three spin zero π's, hence two degrees of freedom are needed to completely describe the system. [1] A convenient choice is to pick any two of the $\pi\pi$ invariant mass squared terms, for example $m^2_{\pi^-\pi^+}$ and $m^2_{\pi^+\pi^0}$ since, when averaged over intermediate spin states, the phase-space for the decay is independent of position in $(m^2_{\pi^-\pi^+}, m^2_{\pi^+\pi^0})$ space. A Dalitz plot is simply a scatter plot of all event candidates in the $(m^2_{\pi^-\pi^+}, m^2_{\pi^+\pi^0})$ plane. Since phase-space is uniform in these variables, any structure that shows up in the Dalitz plot is due entirely to the matrix element of the decay. Intermediate resonances will show up as bands on the Dalitz plot. Loosely stated, the structure within each band tells us about the spin of the resonance, the number of events in each tells us about relative amplitudes, and the regions of overlap between the bands contains information about relative phases.

Figure 1 shows a Dalitz plot of all events passing the analysis selection requirements in this analysis. It is clear that the distribution of events is not uniform. Indeed, bands centered at mass-squared values appropriate for $\rho(770)$ mesons can clearly be seen along both axes. The fact that these bands are not uniform, but rather are populated toward the edges of the plot, indicates that they are due to spin-1 resonances. The narrow uniform band at $m^2_{\pi^-\pi^+} \sim 0.25$ GeV^2 is due to $D^0 \to K^0_S\pi^0$ decays.

[1] Each daughter has 4 degrees of freedom, for a total of 12. Energy and momentum conservation fixes 4 of these. Knowledge of the daughter masses fixes 3 more. Since overall spatial orientation is irrelevant, 3 more are fixed, leaving 2.

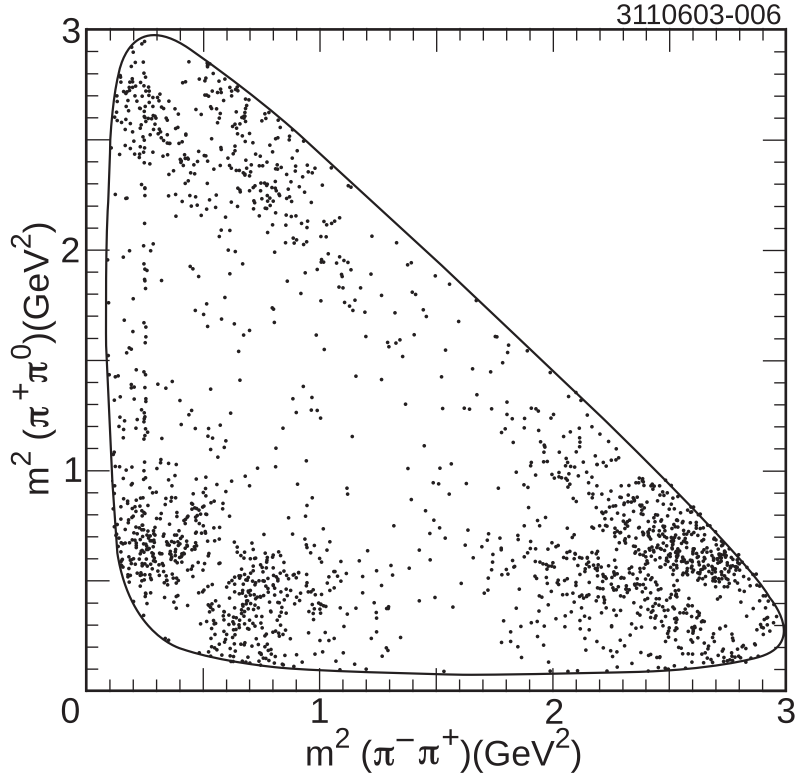

FIG. 1: The $D^0 \to \pi^-\pi^+\pi^0$ Dalitz plot after final event selection.

C. Resonances

The technique used in this analysis is to fit the $(m^2_{\pi^-\pi^+}, m^2_{\pi^+\pi^0})$ event distribution from data with various models containing collections of possible resonant as well as non-resonant contributions. Any non-resonant contribution is assumed to be uniform across the Dalitz plot, and all resonances are represented by a Breit-Wigner lineshape times appropriate factors:

$$\mathcal{M}_{D^0\to(AB)C} = F_{D^0}(q^2)F_{res}(q^2)\frac{A_S}{m^2_{res} - q^2 - im_{res}\Gamma(q)}, \tag{1}$$

where $q^2 = m^2_{AB}$ is the reconstructed invariant mass squared of the (AB) candidate, m_{res} is the nominal mass of the resonance, $F_{D^0}(q^2)$ and $F_{res}(q^2)$ are form-factors[6], and $\Gamma(q)$ is a mass-dependent width.[7] The term in the numerator, A_S, comes from angular momentum considerations and depends on the spin S of the resonance. For spin 0 resonances, $A_0 = 1$, and for spin 1, $A_1 = m^2_{AC} - m^2_{BC} + (m^2_{D^0} - m^2_C)(m^2_B - m^2_A)/m^2_{res}$.

It is unknown, a priori, how much of each possible resonance will be required to fit the data, thus we weigh each Breit-Wigner term in the matrix element with its own amplitude $\mathcal{A}$ and phase ϕ. The total matrix element is simply a sum of the matrix elements for all resonances under consideration in a given model:

$$
\begin{aligned}
\mathcal{M}_{D^0\to\pi^-\pi^+\pi^0} = \; & \mathcal{A}_{non\ res} \times e^{i\ \phi_{non\ res}} \; + \\
& \mathcal{A}_{\rho^+\pi^-} \times e^{i\ \phi_{\rho^+\pi^-}} \times \mathcal{M}_{D^0\to\rho^+\pi^-} \; + \\
& \mathcal{A}_{\rho^-\pi^+} \times e^{i\ \phi_{\rho^-\pi^+}} \times \mathcal{M}_{D^0\to\rho^-\pi^+} \; + \\
& \mathcal{A}_{\rho^0\pi^0} \times e^{i\ \phi_{\rho^0\pi^0}} \times \mathcal{M}_{D^0\to\rho^0\pi^0} \; + \ldots
\end{aligned}
\tag{2}
$$

It is clear from a simple examination of the Dalitz plot shown in Figure 1 that there are at least three resonant contributions to the $D^0 \to \pi^-\pi^+\pi^0$ decay: $\rho^0\pi^0$, $\rho^+\pi^-$, and $\rho^-\pi^+$. Not obvious is the extent to which other resonances may also be contributing, and the level at which a non-resonant component is present. As described below, our procedure was to start with the three $\rho\pi$ resonances and add other components one at a time to see which improved the fit and yielded fit fractions which were not consistent with zero.

The long lifetime of the K^0_S means that the two-body decay $D^0 \to K^0_S\pi^0$ will not interfere with any other resonances, thus we treat the K^0_S as part of the background.

II. ANALYSIS

A. General Overview

We are searching for the following decay chain: [2]

$$
\begin{aligned}
D^{*+} \;\to\; & D^0\, \pi^+_{\mathbf{slow}} \\
& \hookrightarrow \pi^-\,\pi^+\,\pi^0 \\
& \qquad\qquad \hookrightarrow \gamma\,\gamma
\end{aligned}
$$

We require that the D^0 mesons under study come from decaying D^{*+}'s. This additional constraint greatly reduces the background without a large signal loss, and since the charge of π^+_{slow} is correlated to the charge of the charm quark in the D meson, it also provide a method for differentiating between $D^0 \to \pi^-\pi^+\pi^0$ and $\overline{D^0} \to \pi^+\pi^-\pi^0$ which are otherwise indistinguishable.

We first construct π^0 candidates from photon candidates in the electromagnetic calorimeter. Next, we construct D^0 candidates by combining π^0 with pairs of oppositely charged tracks. D^{*+}'s are built by adding π^+_{slow} candidates to the D^0's. Combinatoric background is significantly reduced by demanding that the mass of the D and the $D^* - D$ mass difference both be within one standard deviation of the nominal value, and that the scaled momentum of the D^*, $x_{D^*} = p_{D^*}/p_{D^*,max}$, is greater than 0.7.

B. Dalitz Fitter

To fit the data to the matrix element model shown in Equation 2, we used a MINUIT-based unbinned maximum likelihood fitter, minimizing

$$
\mathcal{F} = \sum_{events} (-2 \ln \mathcal{L}), \tag{3}
$$

[2] Charge conjugation implied throughout.

where

$$\mathcal{L} = \left(F \, \frac{\mathcal{E}(m^2_{\pi^-\pi^+}, m^2_{\pi^+\pi^0}) \, |\mathcal{M}_{D^0\to\pi^-\pi^+\pi^0}|^2}{\mathcal{N}_{signal}} + (1-F) \frac{\mathcal{B}(m^2_{\pi^-\pi^+}, m^2_{\pi^+\pi^0})}{\mathcal{N}_{background}} \right) \tag{4}$$

represents the likelihood that a given candidate is either signal or background as a function of the fit parameters which determine $\mathcal{M}_{D^0\to\pi^-\pi^+\pi^0}$, and

- F is the fraction of signal events in the sample, about 80% in this analysis, obtained by fitting the $D^0 \to \pi^-\pi^+\pi^0$ mass distribution.
- $\mathcal{E}(m^2_{\pi^-\pi^+}, m^2_{\pi^+\pi^0})$ is the efficiency for an event falling at point $(m^2_{\pi^-\pi^+}, m^2_{\pi^+\pi^0})$ in the Dalitz plot to be detected by CLEO and to pass all of our analysis cuts. This shape was determined by fitting a $2D$ cubic polynomial to reconstructed signal Monte Carlo generated uniformly in phase-space.
- $\mathcal{B}(m^2_{\pi^-\pi^+}, m^2_{\pi^+\pi^0})$ is the background level at point $(m^2_{\pi^-\pi^+}, m^2_{\pi^+\pi^0})$. The background shape was studied using data from a $D^{*+} - D^0$ mass difference sideband, and was parameterized by a cubic polynomial plus additional terms representing real K^0_S and ρ meson decays.
- $\mathcal{N}_{signal} = \int \mathcal{E}(m^2_{\pi^-\pi^+}, m^2_{\pi^+\pi^0}) \, |\mathcal{M}_{D^0\to\pi^-\pi^+\pi^0}|^2 d\mathcal{D}P$ is the signal normalization.
- $\mathcal{N}_{background} = \int \mathcal{B}(m^2_{\pi^-\pi^+}, m^2_{\pi^+\pi^0}) d\mathcal{D}P$ is the background normalization.

III. PRELIMINARY RESULTS

The preliminary results shown below represent the full CLEO II.V [8, 9] dataset of 9 fb^{-1}. Figure 2 shows the three binned Dalitz plot projections for both the data and the best fit.

The only significant contribution to the resonant substructure of this decay was seen from the $D^0 \to \rho^+\pi^-$, $D^0 \to \rho^-\pi^+$, and $D^0 \to \rho^0\pi^0$ channels. The preliminary fit results are presented in Table I.

Resonance	Amplitude	Phase(^{o})	Fit Fraction(%)
ρ^+	1. (fixed)	0. (fixed)	$76.5 \pm 1.8 \pm 4.8$
ρ^0	$0.56 \pm 0.02 \pm 0.07$	$10 \pm 3 \pm 3$	$23.9 \pm 1.8 \pm 4.6$
ρ^-	$0.65 \pm 0.03 \pm 0.04$	$-4 \pm 3 \pm 4$	$32.3 \pm 2.1 \pm 2.2$
non res.	$1.03 \pm 0.17 \pm 0.31$	$77 \pm 8 \pm 11$	$2.7 \pm 0.9 \pm 1.7$

TABLE I: Preliminary Fit Results

Adding other resonances to the fit, including a scalar $\sigma(500)$, did not result in a significantly improved likelihood and yielded fit fractions consistent with zero.[3]

[3] Work to produce upper limits is under way.

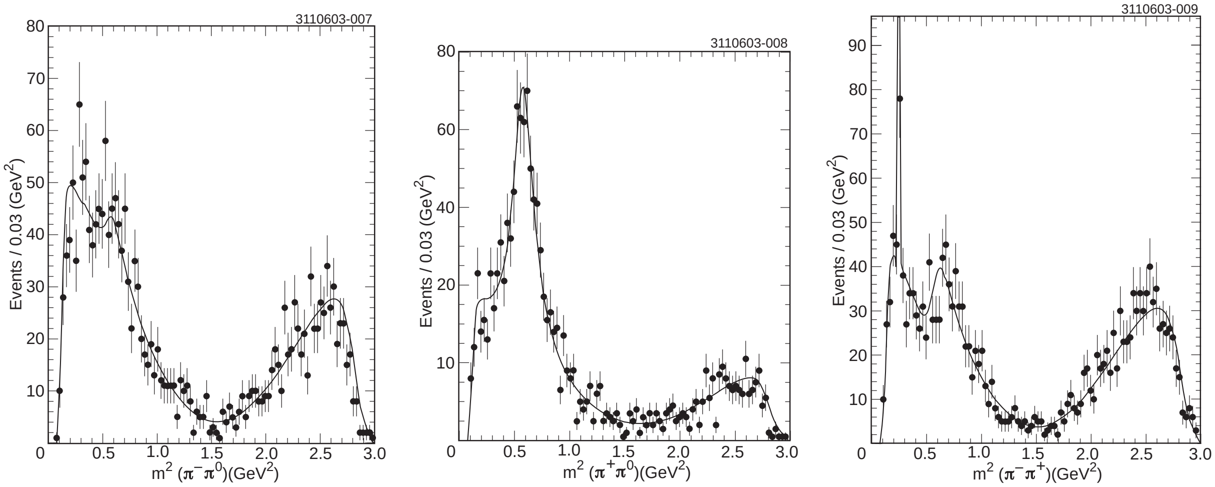

FIG. 2: Projections of the $D^0 \to \pi^-\pi^+\pi^0$ Dalitz plot on the three mass-squared axes. The solid lines are binned projections of the best fit.

In addition, there was no evidence of CP asymmetry, either by comparison of the phases and amplitudes from separate fits to our $D^0 \to \pi^-\pi^+\pi^0$ and $\overline{D^0} \to \pi^+\pi^-\pi^0$ data samples, or in the single calculated figure of merit $\mathcal{A}_{CP} = 0.01^{+0.09}_{-0.07} \pm 0.09$, where

$$\mathcal{A}_{CP} = \int \frac{\left|\mathcal{M}_{D^0}\right|^2 - \left|\mathcal{M}_{\overline{D^0}}\right|^2}{\left|\mathcal{M}_{D^0}\right|^2 + \left|\mathcal{M}_{\overline{D^0}}\right|^2} d\mathcal{D}P \Big/ \int d\mathcal{D}P. \tag{5}$$

We estimate systematic errors by varying parameters of concern and re-running the Dalitz fitter to assess the sensitivity of the results to these variations. This was done for our parameterizations of efficiency and background, our determination of signal fraction, and our event selection criteria. Further systematic studies are ongoing.

IV. CONCLUSIONS

We report preliminary results from our Dalitz analysis of $D^0 \to \pi^-\pi^+\pi^0$. While we find large fit fractions for the three $\rho(770)$ channels $D^0 \to \rho^+\pi^-$, $D^0 \to \rho^-\pi^+$, and $D^0 \to \rho^0\pi^0$, as well as a small but significant non-resonant contribution, we do not find significant contributions from any other resonances including the $\sigma(500)$.

The $\sigma(500)$ remains a controversial particle. E791 found strong evidence for it in their $D^+ \to \pi^-\pi^+\pi^+$ analysis[3], while we find no need for it in $D^0 \to \pi^-\pi^+\pi^0$. This clearly demands further study.

The lack of a contribution from more massive ρ mesons is also worthy of comment. In CLEO's analysis $D^0 \to K^-\pi^+\pi^0$,[2] the $\rho^+(1700)$ had a small yet statistically significant fit fraction. Having observed $D^0 \to K^-\rho^+(1700)$, one might expect to observe $D^0 \to \pi^-\rho^+(1700)$ as well, but we do not. It is interesting to note that in the $D^0 \to K^-\pi^+\pi^0$ analysis, the nominal peak location of the $\rho^+(1700)$ was not on the Dalitz plot so this analysis was only sensitive to the tail of this resonance. In $D^0 \to \pi^-\pi^+\pi^0$, the peak of the $\rho(1700)$ resonances are located within the Dalitz plot, making $D^0 \to \pi^-\pi^+\pi^0$ a potentially

more suitable laboratory for studying these heavy resonances. Again, this begs for further investigation.

Finally, we saw no evidence for CP violation, either from comparing the amplitudes, phases, and fit fractions from the separate $D^0 \to \pi^-\pi^+\pi^0$ and $\overline{D^0} \to \pi^+\pi^-\pi^0$ fits, or in the single $\mathcal{A}_{CP}$ number. Recent theoretical work permits CP violation on the order of 0.1% [4, 5] in this mode, but we do not have sufficient statistics to confront this prediction.

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